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A MATHEMATICAL MODEL FOR DIGITAL GUNFIRE CONTROL USING NUMERICAL INTEGRATION

G. P. Burns, et al

Naval Surface Weapons Center
Dahlgren Laboratory, Virginia

March 1975

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NSWC/DL TECHNICAL REPORT TR-3282
March 1975

A MATHEMATICAL MODEL FOR DIGITAL GUNFIRE CONTROL USING NUMERICAL INTEGRATION

by

G. P. Burns
L. G. Stout, Jr.

Warfare Analysis Department

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FOREWORD

The mathematical model described in this report is an extension of the model described in NWL Technical Report No. TR-3061, dated April 1974. This work was performed in the Aeroballistics and Computer Programming Divisions of the Warfare Analysis Department under Naval Ordnance Station, Louisville, Kentucky, Work Request Number WR-4-0019.

The report was reviewed by D. R. Daniel, Head, Ballistics Analysis Branch, I. V. West, Head, Programming Systems Branch, G. H. Ott, Research Mathematician, Ballistics Analysis Branch, and W. P. Warner, Head, Computer Programming Division.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER TR-3282	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A MATHEMATICAL MODEL FOR DIGITAL GUNFIRE CONTROL USING NUMERICAL INTEGRATION		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. P. Burns L. G. Stout, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center Dahlgren Laboratory Dahlgren, Va. 22448		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE March 1975 13. NUMBER OF PAGES 65
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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S/N 0102-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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A mathematical model developed for digital gunfire control using the NSWC/DL effective drag functions was modified. The NSWC/DL functions were replaced with fourth-order Runge-Kutta numerical integration of particle trajectory equations for calculation of gun elevation angle, projectile deflection, and projectile time of flight. Projectile drag coefficient is obtained during the integration process by table look-up of prestored values. The sequence of computations is given for the present position, prediction, ballistics and gun order sections of the model.

The current version of the modified model was designed not for use in a gunfire control system but as a tool for evaluation of gunfire control models.

CONTENTS

SYMBOLS

FORTRAN Model	Text	
AM	AM	Parameter for each projectile relating change of initial velocity to variation of weight from standard
AX,AY,AZ	AX,AY,AZ	Components of earth's rotation vector in X, Y, and Z directions, respectively
B	B	Angle between ship's centerline and line of sight measured in horizontal plane clockwise from ship's centerline
BD	Bd	Angle between ship's centerline and line of sight measured in deck plane clockwise from ship's centerline
BDGP	Bdg'	Angle between vertical plane through ship's centerline and normal plane through line of fire measured in deck plane
BG	Bg	Angle between ship's centerline and line of fire measured in horizontal plane clockwise from ship's centerline
BGY	Bgy	Azimuth of line of fire measured clockwise from north
BWY	Bwy	Azimuth of direction from which true wind is blowing, measured clockwise from north
BY	By	Azimuth of line of sight in horizontal plane measured clockwise from north
BYTG	ByTg	Azimuth of target at end of dead time
BY2	By2	Azimuth of future position measured in horizontal plane clockwise from north
CANS	CANS	Drift constant for projectile
CM	CM	Mach number of projectile at altitude Z
CO	Co	Azimuth of own ship's course measured clockwise from north

SYMBOLS (Continued)

FORTRAN Model	Text	
CQO	Cqo	Azimuth of own ship's heading measured clockwise from north
CS	CS	Velocity of sound at altitude Z
CSS	CSS	Velocity of sound at standard atmospheric temperature
DCQO	DCqo	Rate of change of ship's heading
DDS	DDS	Correction of ballistic air density for non-standard projectile weight
DEIO	DEio	Rate of change of pitch angle of ship
DEIN(1)	t	Time of projectile in flight
DEIN(2) DEIN(8) DEIN(3)	X,Y,Z	Downrange, cross-range and vertical components of position of projectile in flight. Origin is at the point of firing
DEIN(4) DEIN(9) DEIN(5)	$\dot{X},\dot{Y},\dot{Z}$	Velocity components of projectile in flight
DEIN(6) DEIN(7)	D_{C1},D_{C2}	Drift integrals
DEOUT(1)	$\dot{t}$	Derivative of t with respect to t (equal to 1.0)
DEOUT(2)	$\dot{X}$	DEIN(4)
DEOUT(3)	$\dot{Z}$	DEIN(5)
DEOUT(4) DEOUT(9) DEOUT(5)	$\ddot{X},\ddot{Y},\ddot{Z}$	Components of acceleration of projectile in flight
DEOUT(6)	$\dot{D}_{C1}$	Derivative of D_{C1} with respect to t
DEOUT(7)	$\dot{D}_{C2}$	Derivative of D_{C2} with respect to t
DEOUT(8)	$\dot{Y}$	DEIN(9)

SYMBOLS (Continued)

FORTRAN Model	Text	
DMB	DMb	Ship's speed perpendicular to line of fire
DMBOG	DMbog	Cross-range gun velocity component due to gun throw
DMHAG	DMhag	Gun velocity component perpendicular to ship's centerline due to gun throw
DMHO	DMho	Own ship's speed
DMHOG	DMhog	Gun velocity component along ship's centerline due to gun throw
DMRH	DMrh	Own ship's speed along line of fire
DMRHOG	DMrhog	Horizontal gun velocity component downrange due to gun throw
DMVOG	DMvog	Vertical gun velocity component due to gun throw
DRAGC	DRAGC	Drag coefficient of projectile
DRIFT	DRIFT	Deflection perpendicular to line of fire due to gyroscopic effect on spinning projectile
DS	DS	Ballistic air density (percent of standard x 10^{-2})
DU	DU	Correction of projectile initial velocity for non-standard projectile weight
DW	DW	Variation of projectile weight from standard
DX	DX	Horizontal distance from target future position to projectile
DZ	DZ	Vertical distance from target future position to projectile
DZO	DZo	Rate of change of roll angle of ship
E	E	Stabilized elevation angle of target present position
ED	Ed	Angle between deck plane and line of sight, measured in the vertical plane through line of sight

SYMBOLS (Continued)

FORTRAN Model	Text	
EDGP	Edg'	Angle between deck plane and line of fire, measured in normal plane through line of fire
EG	Eg	Gun elevation angle in stabilized coordinate system
EI	Ei	Angle between the horizontal plane and the deck plane, measured in vertical plane through line of sight
EIO	Eio	Pitch angle of ship
E2	E2	Angle between horizontal plane and line to future target position, measured in vertical plane through line to future target position
E4	E4	Aiming position angle in stabilized coordinate system
G	G	Acceleration due to gravity at sea level
GALT	GALT	Geopotential altitude
GAMMA	GAMMA	Reciprocal ballistic coefficient of projectile
IATM	-	Atmosphere type
ICOR	-	Coriolis type
LDP	Ld'	Angle between vertical plane through line of sight and normal plane through line of fire, measured in deck plane from vertical plane through line of sight
LH	Lh	Angle between line of sight and line of fire measured in horizontal plane
MBG	Mbg	Total linear deflection perpendicular to line of fire
MO	Mode	Mode of operation of fire control system
MTHX	MThx	Horizontal displacement of target in east-west direction during time of flight of projectile

SYMBOLS (Continued)

FORTRAN Model	Text	
MTHY	MThy	Horizontal displacement of target in north-south direction during time of flight of projectile
MTZ	MTz	Vertical displacement of target during time of flight of projectile
MXTG	MxTg	Horizontal displacement of target with respect to gun in east-west direction during dead time
MYTG	MyTg	Horizontal displacement of target with respect to gun in north-south direction during dead time
MZTG	MzTg	Vertical displacement of target with respect to gun during dead time
PDA	Pda	Displacement of gun from centerline of ship, measured in deck plane perpendicular to centerline
PDO	Pdo	Displacement of gun from director along center-line of ship
PHA	Pha	Component of gun parallax in the horizontal plane perpendicular to vertical plane through own ship's centerline
PHO	Pho	Component of gun parallax in the horizontal plane and in the vertical plane through own ship's centerline
PTO	PTO	Equivalent density correction to account for variation of air drag due to projectile-fuze combinations
PV	PV	Vertical displacement of gun above or below director
PVDP	Pvd'	Normal component of gun displacement above deck
PX	PX	East-west displacement of gun from director in horizontal plane
PY	PY	North-south displacement of gun from director in horizontal plane
QEG	qEg	Elevation spot correction
QLH	qLh	Deflection spot correction

SYMBOLS (Continued)

FORTRAN Model	Text	
QRHX	qRhx	Offset of landmark from target in east-west direction
QRHY	qRhy	Offset of landmark from target in north-south direction
QRH4	qRh4	Range spot correction
QSTARH	QSTARH	Horizontal distance of illuminating projectile beyond target
QSTARZ	QSTARZ	Vertical distance of illuminating projectile above target
QHXS	Qhxs	East-west component of QSTARH
QHYS	Qhys	North-south component of QSTARH
R	R	Distance from own ship to target measured along line of sight
RE	RE	Radius of earth in feet
RH	Rh	Projection of present range in horizontal plane by a vertical plane through line of sight
RHO	RHO	Density of atmosphere at altitude ZS or GALT
RH2	Rh2	Projection of R2 in horizontal plane by a vertical plane through R2
RHX2	Rhx2	East-west component of Rh2
RHY2	Rhy2	North-south component of Rh2
RH4	Rh4	Horizontal range to aim point
RV	RV	Vertical range to aim point
RV2	RV2	Height of future position of target above horizontal plane, measured in vertical plane through R2
R2	R2	Distance from gun to future position of target

SYMBOLS (Continued)

FORTRAN Model	Text	
SR	SR	Slant range to projectile in XZ plane
T	T	Air temperature (^{o}K) at altitude ZS
TD	TD	Deviation of surface air temperature from standard (^{o}F)
TG	Tg	Dead time
TK	TK	Surface air temperature (^{o}K)
TM	TM	Surface air temperature (^{o}F)
TOL2	TOL2	Upper limit of absolute value of two successive calculated values of time of flight of projectile
TR	TR	Air temperature (^{o}R) at altitude GALT
TS	TS	Surface air temperature (^{o}F) x 10^{-2}
T4	T4	Projectile time of flight at beginning of dead time
T5	T5	Fuze time (sec)
U	U	Initial ejection velocity of projectile from gun
UCW	UCW	Initial velocity of projectile corrected for variation of projectile weight from standard
V	V	Target speed
VAA	VAA	Velocity of projectile with respect to air
W	W	Standard weight of projectile
WB	Wb	Horizontal component of true wind perpendicular to line of fire
WH	Wh	Horizontal true wind speed
WHX	Whx	East-west component of true wind in horizontal plane

SYMBOLS (Continued)

FORTRAN Model	Text	
WHY	Why	North-south component of true wind in horizontal plane
WRH	Wrh	True horizontal ballistic wind
X,Y,Z	x,y,z	Stabilized components of present position of target with respect to director in east-west, north-south and vertical directions, respectively
X,Y,Z	$\hat{x},\hat{y},\hat{z}$	Estimated stabilized components of present position of target with respect to director
XDDOT YDDOT ZDDOT	$\hat{\ddot{x}},\hat{\ddot{y}},\hat{\ddot{z}}$	Estimated stabilized components of target present acceleration with respect to director
XDOT YDOT ZDOT	$\hat{\dot{x}},\hat{\dot{y}},\hat{\dot{z}}$	Estimated stabilized components of target present velocity with respect to director
XDOTTG YDOTTG ZDOTTG	$\hat{\dot{x}}Tg$ $\hat{\dot{y}}Tg$ $\hat{\dot{z}}Tg$	Estimated stabilized components of target velocity with respect to director at end of dead time
XL	L	Latitude of ship at firing time
XTG YTG ZTG	xTg yTg zTg	Stabilized position components of target with respect to gun after dead time
XW,YW,ZW	XW,YW,ZW	Downrange, cross-range, and vertical components of projectile velocity with respect to air
ZD	Zd	Cross level angle
ZO	Zo	Roll angle
ZS	ZS	Geometric altitude above sea level

Note: Symbols used in this report are, as nearly as possible, consistent with standard fire control symbols published in NAVORD OP 1700, Volume 1.[1]

1. INTRODUCTION

1.1 Background

The existing Gunfire Control System (GFCS) MARK 68[2] uses a MARK 47 analog computer to generate gun orders for the 5-Inch 54-Caliber MARK 42 Gun Mount. Two gunfire control modes, air and surface, are included in the computer operation. The computer uses target present position data, ship and target rates of motion, and ballistic data to determine a line of fire such that the projectile will arrive at the predicted target future position at the end of the projectile time of flight. Gun orders are then computed and transmitted to the gun mount, and fuze-setting order is determined for mechanical time fuzes. Under the MARK 68 Gun Improvement Program personnel at the Naval Surface Weapons Center, Dahlgren Laboratory, worked toward converting the MARK 68 Analog GFCS to a digital system. One result of this work was the development of a mathematical model[3] for digital gunfire control using the NSWC/DL effective drag functions.

In order to develop a more general gunfire control program, the effective drag model has been modified by replacing the NSWC/DL functions with fourth-order Runge-Kutta numerical integration of three-dimensional particle trajectory equations[4] for computation of gun elevation angle, projectile deflection including drift, and projectile time of flight. Terms are included in the particle trajectory equations to account for effects of Coriolis acceleration, wind and ship's motion, and variation of acceleration of gravity with altitude. Drift is obtained by integration of drift integrals. Air density and air temperature are computed using special equations for the U.S. Navy Standard Atmosphere (NAST) or the 1962 U.S. Standard Atmosphere (ICAO) depending on which atmosphere is required in the integration model. Projectile drag coefficients for NAST or ICAO atmosphere are obtained during the integration process by table look-up of values stored in the computer for the projectile of interest.

The model in its current form was designed not for use in a gunfire control system, but as a tool for evaluation of gunfire control systems. It is expected that modifications will have to be made for evaluation of some special features of gunfire control systems, and for certain projectiles which do not have free flight, are not fired at the predicted target future position, or for which the reciprocal ballistic coefficient is a function of gun elevation angle.

To adapt the model for use in a gunfire control system, it would be necessary to perform the ballistic calculations with a more efficient integration scheme than fourth-order Runge-Kutta and to functionalize projectile drag coefficient using, for example, the method described by Duke, et al.[5]

1.2 Objectives

The objectives of this report are to present the sequence of equations used to solve gunfire control problems using numerical integration of particle trajectory equations and to describe the method of interfacing the ballistic equations with the present position, prediction, and gun order sections of the mathematical model.

The next section contains a general description of the modified digital model and the modes of operation. Subsequent sections give the sequence of calculations in the different sections of the model, a detailed description of the ballistic calculations using numerical integration, and a discussion of the accuracy and limitations of the model.

Appendix A contains the FORTRAN computer program, Appendix B a flow diagram, and Appendix C an input guide.

2. GENERAL DESCRIPTION OF THE DIGITAL GUNFIRE CONTROL PROGRAM

2.1 Description

The computations performed in this model follow generally those in Reference 3 except that gun elevation angle, projectile deflection, and projectile time of flight are computed by numerical integration of particle trajectory equations. Stabilized coordinates of target present position are computed. The prediction section uses these with target velocity, target acceleration, and projectile time of flight from the ballistics section to compute stabilized coordinates of future position. The ballistics section uses target future position and ballistic parameters to determine gun elevation angle, horizontal deflection angle and projectile time of flight. Time of flight is fed back to the prediction section, and the computation is recycled until two successive values of time of flight are within a specified tolerance limit.

Fuze time (T5) is taken as projectile time of flight if dead time was used in determining future position.

Values of gun elevation angle and horizontal deflection angle computed at the beginning of dead time are input to the gun order section where gun train order and gun elevation order are computed.

2.2 Modes of Operation

Since the ballistic calculations are accomplished using numerical integration, fire control problems can be solved for each mode of firing any standard projectile for which drag data and the reciprocal ballistic coefficient are available. No distinction is made between air and surface modes. Reduced charge, full charge and super charge computations can be made by using corresponding drag data and proper values for reciprocal ballistic coefficient.

Program branches are provided for both reverse slope and star shell modes. It should be noted that projectile drag characteristics may vary between normal trajectory and high angle firings. These variations will have to be provided by the user. The star shell geometry is described in detail; however, implementation of drag variation after formation of the star must be provided also by the user.

Some modifications would be required for firing a guided projectile, the flight of which is affected by thrust and guidance.

3. PRESENT POSITION SECTION

In the present position section, data measurements from the deck instruments are used to compute stabilized polar coordinates of target present position with respect to the director; stabilized components of gun displacement from director along and perpendicular to the ship's centerline and in the east-west, north-south and vertical directions; and Cartesian coordinates of target present position with respect to the director.

Provisions are made for offset and range spot corrections in the surface mode. Projectile initial velocity and ballistic air density are modified to compensate for variation of projectile weight from standard. Ballistic air density is modified to compensate for special projectile-fuze combinations. East-west and north-south components of true wind, and roll and pitch angles of the ship are computed.

Cartesian coordinates of present position are computed with respect to the director at a given time and used as best estimates of target present position along with velocity and acceleration coordinates from whatever source is available to the user. These estimated values and appropriate parallax components are used to determine coordinates of target position with respect to gun at end of dead time.

Input to the present position section includes range to present position of target (R), director train (Bd), director elevation (Ed), level angle (Ei), cross-level angle (Zd), heading of ship (Cqo), ship's course (Co), ship's speed (DMho), dead time (Tg), east-west offset (qRhx), north-south offset (qRhy), range spot correction (qRh4), gun parallax displacements (Pdo, Pda, and Pvd'), projectile initial velocity (U), standard weight of projectile (W), variation of projectile weight from standard (DW), ballistic air density (DS), equivalent density correction for particular projectile-fuze combinations (PTO), true wind speed (Wh) and direction (Bwy), and constant AM used in correction of projectile initial velocity for variation of projectile weight from standard. Horizontal distances of illuminating projectile from target in the east-west (Qhxs) and north-south (Qhys) directions, and distance of illuminating projectile above target (QSTARZ) are set to zero for applications other than star shell.

The sequence of computations performed in the present position section follows. Symbols are defined in a separate section of this report (see Contents) and are generally the same as those in Reference 3.

$$Eio = \sin^{-1}(\sin Ei \cdot \cos Bd + \cos Ei \cdot \sin Bd \cdot \sin Zd)$$

$$Zo = \sin^{-1}[(\cos Bd \cdot \cos Ei \cdot \sin Zd - \sin Ei \cdot \sin Bd)/\cos Eio]$$

$$B = \tan^{-1}\left[\frac{\sin Bd \cdot \cos Zd}{\cos Bd \cdot \cos Ei - \sin Bd \cdot \sin Ei \cdot \sin Zd}\right]$$

$$By = Cqo + B$$

$$E = Ed - Ei$$

$$Rh = R \cdot \cos E$$

$$x = Rh \cdot \sin By + qRhx$$

$$y = Rh \cdot \cos By + qRhy$$

$$By = \tan^{-1}(x/y)$$

$$B = By - Cqo$$

$$Rh = (x^2 + y^2)^{\frac{1}{2}} + qRh4$$

$$Zd = \sin^{-1}[\sin B \cdot \cos Zo \cdot \sin Eio + \cos B \cdot \sin Zo]$$

$$Ei = \sin^{-1}[(\cos B \cdot \cos Zo \cdot \sin Eio - \sin B \cdot \sin Zo)/\cos Zd]$$

$$Bd = \tan^{-1}[(\cos Ei)/(\cot B \cdot \cos Zd + \sin Ei \cdot \sin Zd)]$$

$$Pho = Pdo \cdot \cos Eio + Pvd' \cdot \sin Eio \cdot \cos Zo + Pda \cdot \sin Eio \cdot \sin Zo$$

$$Pha = Pda \cdot \cos Zo - Pvd' \cdot \sin Zo$$

$$PX = Pho \cdot \sin Cqo + Pha \cdot \cos Cqo$$

$$PY = Pho \cdot \cos Cqo - Pha \cdot \sin Cqo$$

$$PV = Pvd' \cdot \cos Eio \cdot \cos Zo + Pda \cdot \sin Zo \cdot \cos Eio - Pdo \cdot \sin Eio$$

$$x = Rh \cdot \sin By$$

$$y = Rh \cdot \cos By$$

$$z = R \cdot \sin E$$

x, y and z are stabilized Cartesian present position coordinates of the target with respect to the director at a given time. These are input as best estimates of target present position $(\hat{x},\hat{y},\hat{z})$ along with velocity $(\dot{x},\dot{y},\dot{z})$ and acceleration $(\ddot{x},\ddot{y},\ddot{z})$ coordinates from whatever source is available to the user.

$$DU = -AM \cdot DW \cdot U/W$$

$$DDS = -DS \cdot DW/W$$

$$UCW = U + DU$$

$$DS = DS + DDS + PTO/100$$

$$Whx = -Wh \cdot \sin Bwy$$

$$Why = -Wh \cdot \cos Bwy$$

$$MxTg = \hat{\dot{x}} \cdot Tg + \tfrac{1}{2} \cdot \hat{\ddot{x}} \cdot Tg^2$$

$$MyTg = \hat{\dot{y}} \cdot Tg + \tfrac{1}{2} \cdot \hat{\ddot{y}} \cdot Tg^2$$

$$MzTg = \hat{\dot{z}} \cdot Tg + \tfrac{1}{2} \cdot \hat{\ddot{z}} \cdot Tg^2$$

$$xTg = \hat{x} + MxTg - PX$$

$$yTg = \hat{y} + MyTg - PY$$

$$zTg = \hat{z} + MzTg - PV$$

$$ByTg = \tan^{-1} (xTg/yTg)$$

4. PREDICTION SECTION

The future position of the target is the target position with respect to the gun at the end of the time of flight of the projectile. It is obtained by adding the displacement of the target during the time of flight to the position of the target with respect to the gun at the end of dead time. In normal modes of operation (i.e., other than star shell), the projectile is delivered to the future position of the target. In the star shell mode, the projectile is delivered to some point beyond and above the threat depending upon the projectile being used and the desired result.

The sequence of computations performed in the prediction section follows.

$$V = (\hat{\dot{x}}^2 + \hat{\dot{y}}^2 + \hat{\dot{z}})^{\frac{1}{2}}$$

$$T4 = R/(U + V)$$

$$\hat{\dot{x}}Tg = \hat{\dot{x}} + \hat{\ddot{x}} \cdot Tg$$

$$\hat{\dot{y}}Tg = \hat{\dot{y}} + \hat{\ddot{y}} \cdot Tg$$

$$\hat{\dot{z}}Tg = \hat{\dot{z}} + \hat{\ddot{z}} \cdot Tg$$

$$MThx = \hat{\dot{x}}Tg \cdot T4 + \tfrac{1}{2} \cdot \hat{\ddot{x}} \cdot T4^2 + DMho \cdot T4 \cdot \sin Co$$

$$MThy = \hat{\dot{y}}Tg \cdot T4 + \tfrac{1}{2} \cdot \hat{\ddot{y}} \cdot T4^2 + DMho \cdot T4 \cdot \cos Co$$

$$MTz = \hat{\dot{z}}Tg \cdot T4 + \tfrac{1}{2} \cdot \hat{\ddot{z}} \cdot T4^2$$

For star shell, recompute MThx and MThy, and compute Qhxs and Qhys.

$$MThx = (\hat{\dot{x}}Tg + DMho \cdot \sin Co) \cdot (T4 + 30) + \tfrac{1}{2} \cdot \hat{\ddot{x}} \cdot (T4 + 30)^2 - Whx \cdot 30$$

$$MThy = (\hat{\dot{y}}Tg + DMho \cdot \cos Co) \cdot (T4 + 30) + \tfrac{1}{2} \cdot \hat{\ddot{y}} \cdot (T4 + 30)^2 - Why \cdot 30$$

$$x' = xTg + (30 + T4) \cdot \hat{\dot{x}}Tg + \tfrac{1}{2} \cdot \hat{\ddot{x}} \cdot (30 + T4)^2$$

$$y' = yTg + (30 + T4) \cdot \hat{\dot{y}}Tg + \tfrac{1}{2} \cdot \hat{\ddot{y}} \cdot (30 + T4)^2$$

$$R' = (x'^2 + y'^2)^{\frac{1}{2}}$$

QSTARZ = 2000, QSTARH = 5400.

(Values of QSTARZ and QSTARH may be varied as desired)

$$Qhxs = QSTARH \cdot x'/R'$$

$$Qhys = QSTARH \cdot y'/R'$$

The star shell equations above are for the 5-Inch 54 Caliber MARK 48 Illuminating Projectile; introduction of other rounds may require a different sequence of equations.

The equations below are for all projectiles and modes of firing. For projectiles other than star shell, Qhxs = Qhys = QSTARZ = 0.

$$Rhx2 = xTg + MThx + Qhxs$$

$$Rhy2 = yTg + MThy + Qhys$$

$$RV2 = zTg + MTz + QSTARZ$$

$$By2 = \tan^{-1}(Rhx2/Rhy2)$$

$$R2 = \left[(Rhx2)^2 + (Rhy2)^2 + (RV2)^2\right]^{1/2}$$

$$E2 = \sin^{-1}(RV2/R2)$$

5. BALLISTICS SECTION

The ballistics section uses future position coordinates, projectile constants, projectile drag coefficients and other input quantities shown below to calculate gun bearing, horizontal deflection angle, gun elevation angle and projectile time of flight. Gun elevation angle, projectile time of flight, and projectile deflection are calculated by fourth-order Runge-Kutta integration of three-dimensional particle trajectory equations.(4) Time of flight is fed back to the prediction section and calculations are repeated until two successive values of time of flight are within a specified tolerance. When this condition is satisfied, time of flight is taken as fuze time. The calculation is repeated for the present position of the ship, using Tg equal to zero, to obtain values for calculation of gun orders.

Output from the ballistics section includes horizontal deflection angle (Lh) and gun elevation angle (Eg) to the gun order section, and time of flight (T4) to the prediction section.

5.1 Input Not Available From Present Position and Prediction Sections

Input to the ballistic section that is not generated in the present position and prediction sections includes air temperature (TS), earth constants (L,G), tolerance used in obtaining solutions of gun train angle and time of flight of projectile (TOL2), projectile drift constant (CANS), and rates of pitching (DEio), rolling (DZo), and yawing (DCqo) of the ship.

RV is set equal to RV2 and the initial value of Bgy is taken as By2.

Horizontal range to aim point and aiming position angle are given by

$$Rh4 = Rh2 \cdot \cos(Bgy - By2)$$

and

$$E4 = \tan^{-1}(RV/Rh4),$$

respectively.

5.2 Gun Velocity Components Due to Gun Throw

Gun throw is the linear velocity of the gun resulting from rolling, pitching and yawing of the ship. The components of this velocity along and perpendicular to the centerline of the ship

are

$$DMhog = PV \cdot DEio - Pha \cdot DCqo$$

and

$$DMhag = -PV \cdot DZo + Pho \cdot DCqo,$$

respectively.

The components downrange, cross-range and vertical, due to gun throw, are

$$DMrhog = DMhog \cdot \cos Bg + DMhag \cdot \sin Bg,$$

$$DMbog = DMhag \cdot \cos Bg - DMhog \cdot \sin Bg,$$

and

$$DMvog = -Pho \cdot DEio + Pha \cdot DZo,$$

respectively, where

$$Bg = Bgy - Cqo.$$

Initial velocity is recalculated to correct for the effects of gun throw using

$$U = [(UCW \cdot \cos Eg + DMrhog)^2 + (UCW \cdot \sin Eg + DMvog)^2]^{\frac{1}{2}}.$$

5.3 Wind and Ship Velocity Components

Components of true wind, downrange and cross-range, are

$$Wrh = Why \cdot \cos Bgy + Whx \cdot \sin Bgy$$

and

$$Wb = -Why \cdot \sin Bgy + Whx \cdot \cos Bgy,$$

respectively.

Components of the velocity of the ship downrange and cross-range are

$$DMrh = DMho \cdot \cos (Co - Bgy)$$

and

$$DMb = DMho \cdot \sin (Co - Bgy),$$

respectively.

5.4 Gun Elevation Angle, Projectile Deflection, and Projectile Time of Flight

The slant range to the aim point is

$$SR4 = (Rh4^2 + RV^2)^{\frac{1}{2}}$$

An approximate value of gun elevation angle is given by

$$Eg = \tan^{-1}(RV/Rh4) + 0.5 \sin^{-1}(ANG)$$

where

$$ANG = 64.4 \cdot Rh4/U^2.$$

If ANG > 1., set ANG = 1.0. For high angle or reverse slope firing,

$$Eg = \pi/2 - Eg.$$

Initialize $\dot{t} = 1.$, $t = 0.$, $X = 0.$, $Y = 0.$, $Z = 0.$, $\dot{X} = U \cdot \cos Eg + DMrh$, $\dot{Y} = DMb + DMbog$, $\dot{Z} = U \cdot \sin Eg$, $D_{c1} = 0.$, and $D_{c2} = 0.$ X, Y, Z and $\dot{X}$, $\dot{Y}$, $\dot{Z}$ are position and velocity components of the projectile, respectively. X is positive down range, Y is positive to the right as seen from the point of firing, and Z is positive upward.

The downrange, cross-range, and vertical components of velocity of the projectile relative to the air are

$$XW = \dot{X} - Wrh, \quad YW = \dot{Y} - Wb$$

and $ZW = \dot{Z}$, respectively. The velocity of the projectile relative to the air is

$$VA = [(XW)^2 + (YW)^2 + (ZW)^2]^{\frac{1}{2}}.$$

Air temperature, air density, and velocity of sound are required at each step in the numerical integration of the trajectory equations. These are calculated for the desired atmosphere (NAST or ICAO) using equations given below.

<u>NAST Atmosphere</u>

Surface air temperature is given in degrees Kelvin by

$$TK = 5 \cdot TM/9 + 255.23$$

where $TM = 100 \cdot TS$.

Temperature and velocity of sound at geometric altitude ZS above sea level are given by

$$T = TK - 0.001982 \cdot ZS$$

and

$$CS = CSS \cdot (T/288)^{\frac{1}{2}},$$

respectively, where

$$ZS = Z + X^2/(41812000).$$

Z is geometric altitude above the tangent plane at the point of firing the projectile.

Density of the atmosphere at altitude ZS is given in terms of NAST ballistic air density (DS) by

$$RHO = 0.07513 \cdot EXP\,(-0.0000031582 \cdot ZS) \cdot DS.$$

<u>ICAO Atmosphere</u>

Formulas for temperature, pressure, and density of the ICAO atmosphere are given in Reference 6. Constants were determined by Loren J. McAnelly (NSWC/DL) for a modified version of these, and are given below for several ranges of altitudes. Symbols have been changed to conform to usage in this report.

Values are given in terms of geopotential altitude (GALT) where GALT = RE · ZS/ (RE + ZS). RE is radius of the earth, 20855531 feet, and ZS = Z + X^2/(41812000).

Standard temperature (TR) and standard pressure (P) at altitude GALT are computed as follows for different ranges of geopotential altitude:

$-5000 \le GALT < 36089$ feet

$$TR = 518.67 - 0.00356616 \cdot GALT$$

$$P = 1013.25\,(518.67/TR)^{-5.255877}$$

$36089 \le GALT < 65616.8$ feet

$$TR = 389.97$$

$$P = 226.32\,EXP\,[-0.0000480634(GALT-36089.239)]$$

$65616.8 \le GALT < 104986$ feet

$$TR = 389.97 + 0.00054864\ (GALT-65616.789)$$

$$P = 54.7487\ (389.97/TR)^{34.16319}$$

TR is in degrees Rankine and P is in millibars.

Standard air density for the geopotential altitude range $-5000 \le GALT < 104986$ feet is given, in pounds per cubic foot, by

$$RHO = 0.0391462\ (P/TR).$$

For nonstandard ICAO ballistic density (DS)

$$RHO = RHO \cdot DS.$$

Velocity of sound at altitude GALT is given by

$$CS = 1116.49\ \left[(TR + TD)/(518.67)\right]^{1/2}$$

where TD is deviation of surface air temperature from standard in degrees Fahrenheit. Mach number is computed for either NAST or ICAO atmosphere using

$$CM = VA/CS.$$

The projectile drag coefficient (DRAGC) is obtained as a function of Mach number, for the atmosphere being used, by table look-up of values stored in the computer.

The equations of motion of the projectile in three dimensions are

$$\ddot{X} = CONS \cdot XW - (AY \cdot \dot{Z} - AZ \cdot \dot{Y}) - G \cdot X/RE,$$

$$\ddot{Y} = CONS \cdot YW - (AZ \cdot \dot{X} - AX \cdot \dot{Z}) - G \cdot Y/RE,$$

and

$$\ddot{Z} = CONS \cdot ZW - (AX \cdot \dot{Y} - AY \cdot \dot{X}) - G(1 - 2Z/RE)$$

where

$$AX = -0.00014584 \cdot \cos L \cdot \cos Bgy,$$

$$AY = +0.00014584 \cdot \cos L \cdot \sin Bgy,$$

and

$$AZ = -0.00014584 \cdot \sin L.$$

$$RE = 20855531 \text{ feet and}$$

$$CONS = -\pi/8 \cdot GAMMA \cdot RHO \cdot VA \cdot DRAGC/144.$$

GAMMA is the reciprocal ballistic coefficient of the projectile.

Projectile drift is obtained from the solutions of the equations

$$\dot{D}_{c1} = 1/VA^2 \text{ and } \dot{D}_{c2} = X/VA^2.$$

Integration of the trajectory and drift equations to X = Rh4 (Z = RV for reverse slope) yields values of $\dot{X}$, $\dot{Y}$, $\dot{Z}$, D_{c1}, D_{c2}, X, Y, Z and t. The integration method used is standard fourth-order Runge-Kutta with a fixed integration interval.

Drift is computed using

$$DRIFT = CANS\ (X \cdot D_{c1} - D_{c2})$$

where CANS is the drift constant for the projectile.

Let DZ = RV - Z (DX = Rh4 - X for reverse slope) and $SR = (X^2 + Z^2)^{\frac{1}{2}}$;

then

$$Eg = Eg + \tan^{-1}[DZ \cdot (\cos E4)/SR].$$

(For reverse slope $Eg = Eg + \tan^{-1}[DX \cdot (\cos Eg)/Rh4]$.)

The integration is repeated using the new value of Eg until DZ (DX for reverse slope) is less than some preassigned value (say 0.1 ft). When this condition is satisfied, set T4 = t and compute deflection of the projectile perpendicular to the line of fire using

$$Mbg = Y + DRIFT.$$

5.5 Computation of Train Angle and Horizontal Deflection Angle

The gun train angle in the horizontal plane is the azimuth of the line of fire measured clockwise from north. It is the sum of the azimuth of the target future position (By2) and the negative of the angle (DBy) required to compensate for deflection of the projectile in flight. The train angle is given by

$$Bgy = -DBy + By2$$

where

$$DBy = \tan^{-1}(Mbg/Rh4)$$

When the train angle is computed, the horizontal deflection angle (Lh) is obtained from the equation

$$Lh = Bgy - ByTg$$

Lh is used in computation of gun orders.

Time of flight is fed back to the prediction section and the computation loop is recycled until two successive values of time of flight are within a given tolerance (TOL2). When this condition is met, T5 is set equal to T4 if future position was predicted at the end of dead time. If future position was predicted at the beginning of dead time using Tg = 0, Eg and Lh are output to the gun order section and gun orders are computed.

The method of closure of the solution for time of flight of the projectile is described in Reference 3, Appendix J.

6. GUN ORDER SECTION

6.1 Fuze Time

When future position is predicted at the end of dead time, the projectile flight time (T4) is taken as fuze time (T5).

6.2 Gun Orders

Lh and Eg are corrected by adding deflection (qLh) and elevation (qEg) spot corrections, if available.

Then

$$Lh = Lh + qLh$$

and

$$Eg = Eg + qEg.$$

Gun elevation order is computed by substituting values of Lh and Eg into the equation

$$Edg' = \sin^{-1}\left[-\sin Zd \cdot \sin Lh \cdot \cos Eg + \cos Zd \cdot (\sin Ei \cdot \cos Eg \cdot \cos Lh + \sin Eg \cdot \cos Ei)\right].$$

To obtain gun train order, compute

$$Ld' = \tan^{-1}\left[\frac{\cos Zd \cdot \sin Lh \cdot \cos Eg + \sin Zd \cdot (\sin Ei \cdot \cos Eg \cdot \cos Lh + \sin Eg \cdot \cos Ei)}{\cos Eg \cdot \cos Ei \cdot \cos Lh - \sin Eg \cdot \sin Ei}\right];$$

then

$$Bdg' = Ld' + Bd.$$

7. ACCURACY OF MODEL

Accuracy of the numerical integration gunfire control model has been checked for static targets against range tables and standard particle models, and for moving targets against the effective drag model[3] and OP 3729[2] results.

Typical results of the range table comparison are shown below for standard conditions.

Range (Ft)	Time of Flight (Sec) Range Table	Time of Flight (Sec) Numerical Integration Model	Gun Elevation Angle (Min) Range Table	Gun Elevation Angle (Min) Numerical Integration Model
6000	2.55	2.549	57.5	57.6
12000	5.44	5.440	125.6	125.6
18000	8.75	8.749	207.2	207.3
24000	12.57	12.571	306.4	306.6
36000	22.23	22.235	581.0	581.3
42000	28.15	28.154	770.2	770.6
45000	31.30	31.304	879.1	879.5

Comparison of the model with a standard particle model is shown below for nonstandard conditions.

Range (Yds)	Position Angle (Deg)	Time of Flight (Sec) Particle Model	Time of Flight (Sec) Numerical Integration Model	Gun Elevation Angle (Min) Particle Model	Gun Elevation Angle (Min) Numerical Integration Model
5527.0	78.87	8.11	8.114	4768.8	4769.2
6482.7	34.23	9.90	8.898	2253.6	2253.8
7678.7	7.52	11.10	11.099	704.4	704.0
11890.7	2.61	19.39	19.393	619.2	619.1

These tabulations demonstrate that the numerical integration gunfire control model duplicates results given in the range table and those computed using a standard particle model.

In NAVORD OP 3729[2] problems are provided for A-Tests for the Gunfire Control System MARK 68 MOD 13 firing the 5-Inch projectile MARK 41 with VT fuze MARK 73. Among these are twelve AA-800 (target speeds to 800 knots) and eight AA-2000 (target speeds to 2000 knots) problems numbered 11 - 22 and 26 - 33, respectively. For each problem own ship data, target data, atmospheric data and ballistic corrections are given. Solutions are given for each problem for fuze setting (T5), gun train order (BDG'). and gun elevation order (Edg').

The twenty AA problems were solved, without Coriolis effects, by the mathematical model described in this report. Solutions were obtained for no Coriolis acceleration because solutions given in OP 3729 neglected Coriolis effects. For each problem T5, Bdg' and Edg' were computed. Table 1 compares these solutions with those given in OP 3729 and with those obtained using the mathematical model described in Reference 3. The columns of the table show for each problem the deviation of the OP results and the results obtained with the digital model[3] from the results obtained with this model which solves ballistics by numerical integration of particle trajectory equations. Root-mean-square and average values of the differences are given at the bottom of each column.

The root-mean-square values for deviation of the digital model from results of numerical integration are about twenty to forty percent of those for deviation of the OP results from numerical integration. This is consistent with conclusions in Reference 3. Average values of the deviations for the digital model are less than half those for the OP.

Results in Table 1 indicate close agreement between the digital model[3] and the numerical integration model. In view of this agreement, it can be safely concluded that the numerical integration model computes the correct gun orders for the A-Test problems.

Additional checks on the accuracy of the model including computation of Coriolis effects are reported in Reference 7.

TABLE 1

DEVIATIONS OF OP AND DIGITAL MODEL SOLUTIONS OF A-TEST, AA MODE GUNFIRE CONTROL PROBLEMS FROM SOLUTIONS OBTAINED BY NUMERICAL INTEGRATION

(No Coriolis)

A-Test Problem	T5(Sec) Deviation From Numerical Integration		BDG′(Min) Deviation From Numerical Integration		EDG′(Min) Deviation From Numerical Integration	
	OP 3729	Digital Model	OP 3729	Digital Model	OP 3729	Digital Model
11	-.001	.004	-.1	.3	1.5	.2
12	.028	-.001	3.3	.5	-3.5	-.5
13	.039	-.003	1.7	.3	.8	.0
14	.020	.000	.0	.2	-.1	.2
15	-.002	-.008	-1.2	2.9	-.7	-.9
16	.008	-.006	-.6	.4	1.4	-.7
17	.015	-.008	.0	.4	1.4	-.5
18	.005	-.006	.3	-.6	.0	-.1
19	-.008	.006	.1	.0	-.2	-.1
20	-.001	.008	.1	-.5	.3	-.1
21	.021	-.002	-1.8	.8	.8	.0
22	.013	-.009	-1.2	.2	1.2	-.7
26	.029	-.002	.5	-.9	.1	.1
27	.028	-.003	3.8	-1.1	-.4	-1.1
28	-.001	.013	-1.8	-2.0	.3	-.5
29	.004	-.003	-1.3	-.4	-1.1	-.1
30	.043	.007	-.7	-1.1	.9	-.4
31	.028	.020	-7.9	-.4	7.2	3.7
32	-.009	-.002	-5.9	-.1	-2.2	-.2
33	.021	-.005	.5	.2	1.0	.2
RMS	.021	.007	2.6	1.0	3.9	.9
AV*	.016	.006	1.6	.7	1.3	.5

*Average of absolute values.

8. DISCUSSION

With this mathematical model, problems may be solved using either NAST or ICAO atmosphere. It is necessary to use drag data and ballistic density corresponding to the chosen atmosphere.

To compute gun orders for star shell and guided projectiles, the numerical integration model would have to be modified. Modifications of the model would be required, also, to check special characteristics of some gunfire control systems.

For some projectiles, the reciprocal ballistic coefficient is a function of gun elevation angle. A program change would be required to compute gun orders for such a projectile.

Prior to the writing of this report, the numerical integration gunfire control model described herein was used, with excellent results, to predict gun orders for evaluation of the Coastal Patrol and Interdiction Craft (CPIC) gunfire control system. It is felt that this working validation and the results reported in Section 7 constitute an acceptable checkout for the model to allow it to be used as a system design tool.

REFERENCES

1. Standard Fire Control Symbols, NAVORD OP 1700 (Volume 1) Change 3, 15 December 1965.

2. Computer MARK 47 MOD 11, Description, Operation and Maintenance, NAVORD OP 3729 Volumne 1, 1 July 1969

3. Burns, G. P., Kee Soon Chun and L. G. Stout, Jr., A Mathematical Model for Digital Gunfire Control Utilizing the NWL Effective Drag Functions, NWL Technical Report TR-3061, April 1974.

4. McAnelly, L. J., and Russell Cuddy, Weather Coding; request for, Naval Weapons Laboratory Letter, KBB:LJM:RDC:emj, 14 March 1961.

5. Duke, Arthur A., Thomas H. Brown, Kenneth W. Burke and Richard B. Seeley, A Ballistic Trajectory Algorithm for Digital Airborne Fire Control, NWC TP 5416, Naval Weapons Center, China Lake, California, September 1972.

6. U.S. Standard Atmosphere, 1962, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

7. Burns, G. P., and L. G. Stout, Jr., Computation of Coriolis Effects by the NSWC/DL Effective Drag Model for Gunfire Control, NSWC/DL Technical Report TR-3261, January 1975.

APPENDIX A

PROGRAM LISTING

```
      OVERLAY(ABS,0,0)
      PROGRAM PREOTT(INPUT,OUTPUT)
      COMMON/ONE/MO,IATM
      COMMON/THREE/CM,DRAGS,DPAG(144),VAA(144),TOD
      COMMON/FIVE/PNAME
      COMMON/SEVEN/U,DMRH
      COMMON/EIGHT/IFLAG
      COMMON/NINE/DS
      COMMON/TEN/IPRNT
      COMMON/ELEVEN/WB,AX,AY,AZ,XL,BGY,B4B,DMBDG,MBG,CANS,GAMMA
      COMMON/TWELVE/G,CSS,IDOR
      DIMENSION RA(51),TA(51)
      DIMENSION T50P(50),BDGPOP(50),EDGPOP(50),NO(50),NEME(10)
      DIMENSION  TST1(9), TST2(9)
      DIMENSION NAME(2),NOME(4)
      DIMENSION SPEED(3)
      REAL MXTG,MYTG,MZTG,MTHX,MTHY,MTZ,MXTG,MYTG,MZTG   ,LDF    ,MBG,LH
      REAL N,LHN
      DATA TST1/33600.,25500.,54000.,27000.,43500.,21000.,22500.,27000.,
     1 63000./
      DATA TST2/3*0.,21000.,5*0./
      DATA RA,TA/4*0.0/
      DATA TOL2/.005/
      DATA NAME/4HNAST,4HICAO/
      DATA NOME/10HNO CORIOLI, 1HS,10HWITH CORIO,3HLIS/
*  PRESENT POSITION--ANGULAR INPUTS IN DEGREES,DISPLACEMENTS IN FEET
      READ 2000,PNAME
 2000 FORMAT(A4)
      READ 1005,CANS,GAMMA,G,CSS,AM,PTO
      PRINT 1004,CANS,G
 1004 FORMAT(*1BALLISTIC DATA*,/,* CANS=*,F10.5,/,* G=*,F10.5,//)
      PRINT 1010,AM,PTO
 1010 FORMAT(* AM = *,F10.5,/,* PTO = *,F10.5)
      READ 1006,NX
 1006 FORMAT (I5)
```

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```
      READ 1005,(VAA(I),I=1,NX)
      READ 1005,(DRAG(I),I=1,NX)
      PRINT 1003
      DO 1001 I=1,NX
 1001 PRINT 1002,I,VAA(I),DRAG(I)
 1003 FORMAT(* DRAG DATA*)
 1002 FORMAT(* *,I5,2X,2(F10.4,2X))
 1005 FORMAT(12F6.4)
      READ 99,MO
      READ 99,IATM
      READ 99,ICOR
      READ 99,IPRNT
      READ 99,IJIO
      READ 99,NUMB
      IF(IPRNT.LE.2)PRINT 107,NEME(MO)
      IF(IPRNT.LE.2)PRINT 1007,NAME(IATM),NOME(ICOR),NOME(ICOR+1)
   99 FORMAT (14I5)
      IF(IPRNT.LE.2) PRINT 160
  160 FORMAT(*1*,T16,*T5(SECONDS)*,T42,*BDGP(MIN)*,T65,*EDGP(MIN)*,
     1 T85,*COMPUTE*,T98,*COMPUTE ITERATIONS*,/,T3,*ATEST*,T11,
     2 *-------------------*,T36,*--------------------*,T61,
     3 *--------------------*,T87,*TIME*,T98,*------------------*,/,
     4 T2,*PROBLEM*,2X,3(*   OP    DIGITAL DIFF*,5X),*(SECONDS)*,
     5 T99,*T2    T5 *,9X,*MO*,3X,*J*,/)
      IF(IPRNT.LE.2) PRINT 162
  162 FORMAT(*0ND*,5X,*XDR*,7X,*YDR*,7X,*WDR*,7X,*WCR*,7X,*DELXO*,
     1  5X,*OCMEGA*,5X,*RV2*,5X,*T4/T5*,7X,*BGY*,7X,*EG*,7X,*XIV*,
     2  7X,,*YIV*,7X,*ZIV*)
      DO 150 INUM=1,NUMB
      IFLAG=0
      READ 99,NO(INUM)
      IF(IPRNT.EQ.5) PRINT 400,NO(INUM),PNAME,AM,CANS,       NAME(IATM),
     1  G,                       NEME(MO),NOME(ICOR),NOME(ICOR+1)
  400 FORMAT(*1*,6X,*PROBLEM *,I3/*0*,8X,  *GENERAL PROBLEM DESCRIPTION*
     A/*+*8X*___________________________*
```

```
1/* *,10X,A5,1X,*PROJECTILE, AM=*F5.2 *, CANS=*F7.2
2/* *,10X,A5,1X,*ATMOSPHERE, GRAV=*F7.4
3/* *,10X,A10,* MODE*
4/* *,10X,2A10)
 READ 100,XO,YO,CO,DMHO,ED,EI,U,PDO,PDA,PVDP,R,DS,TS,TGG,W,WH,ZD,
1 ZDOT,XDOT,YDOT,T50P(INUM),EDGPOP(INUM),BDGPOP(INUM)
 D=EIO=ZO=XDDOT=YDDOT=ZDDOT=XL=0.0
 DW=V45=HG=DEIO=DSQO=TH=DZO=0.0
 QRHX=QRHY=QLH=QFG=QRH=0.0

 VELO=SQRT(XDOT*XDOT+YDOT*YDOT+ZDOT*ZDOT)*3./1.689
 DATA  SPEED/3H80 KNOTS,9H800 KNOTS,10H2000 KNOTS/
 IF(VELO.LE.80.)IA=1
 IF((VELO.GT.80.).A.(VELO.LE.800.))IA=2
 IF (VELO.GT.800.)IA=3
 DIDIV=DIDRHO=0.0
 IF(IDID.EQ.1)GO TO 5000
 IF(MO.EQ.1)GO TO 4000
 IF(MO.EQ.3)GO TO 4100
 IF(MO.EQ.4) GO TO 4150
 IF(MO.EQ.10)GO TO 4200
 GO TO 5000
4000 CONTINUE
 DIDIV=20.
 DIDRHO=-2.
 GO TO 5000
4100 CONTINUE
 IF(R.LE.6000)DIDIV=10.
 IF((R.GT.6000.).A.(R.LE.12000.))DIDIV=30.
 IF((R.GT.12000.).A.(R.LE.18000.))DIDIV= 50.
 IF(R.GT.18000.) DIDIV=55.
 GO TO 5000
4150 CONTINUE
 DIDRHO=-3.
 DIDIV=11.
```

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```
      IF(R.GT.5000.)  DIDRHO=-3.
      IF(R.GT.5000.)DIDIV=25.
      GO TO 5000
 4200 CONTINUE
      DIDRHO=6.
      IF(R.LE.6000.)DIDIV=-15.
      IF((R.GT.6000.).A.(R.LE.12000.))DIDIV=-30.
      IF((R.GT.12000.).A.(R.LE.18000.))DIDIV=-60.
      IF(R.GT.18000.) DIDIV=-75.
 5000 CONTINUE
CCC WHEN IDIG=3 DIDIV AND DIDRHO ARE ACTUALLY USED IN THE CALCULAAIONS
      IF(IDIG.EQ.3) U=U+DIDIV
      IF(IDIG.EQ.3) DS=DS+DIDRHO
  131 FORMAT(* *8X*MK47 SET UP INFORMATION*,
     A/*+*8X*___________________________*
     1/* *10X*COMPUTER MODE = *  A10,2X,A10,
     2/* *10X*DIDRHO = * F6.2,
     3/* *10X*DIDIV = * F6.2 )
      PRINT 131,NEME(MO),SPEED(IA),DIDRHO,DIDIV
      IF(IPRNT.NE.5) GO TO 130
      COB=CO/AA
      DMHXT=DMHO*SIN(COB)+XDOT*3./BB
      DMHYT=DMHO*COS(COB)+YDOT*3./BB
      DMHT=SQRT(DMHXT*DMHXT+DMHYT*DMHYT)
      CT=0.0
      IF((DMHXT.EQ.0.0).A.(DMHYT.EQ.0.0)) GO TO 129
      CT=ATAN2(DMHXT,DMHYT)*AA
  129 CONTINUE
      IBD =BD
      DBD =(BD-IBD)*60.
      ICO =CO
      DCO =(CO-ICO)*60.
      IED =ED
      DED =(ED-IED)*60.
      IEI =EI
```

```
      DEI  =(EI-IEI)*60.
      IZD  =ZD
      DZD  =(ZD-IZD)*60.
      DELU=U-2500.      $  DELUPD  =DELU+DIDIV
      XRHO=DS-100.      $  XRHOPD  =XRHO+DIDRHO
      PRINT  132,BD,IBD,DBD,BWY,CO,ICO,DCO,CT,DELU,DELUPD,DMHO,DMHT,
     1          ZDOT,XDOT,YDOT,ED,IED,DED,EI,IEI,DEI,U,QEG,QLH
      PRINT  133,QRH4 ,    QRHX,QRHY,R,TGG,W,WH,XRHO,XRHOPD,TS,ZD,IZD,DZD
  132 FORMAT(* *3X*INPUT*,
     A/*+*3X*_____*
     1/*  *10X*BD      DIRECTOR BEARING     *F9.2* DEG,*I4* DEG *F5.1* MIN*
     2/*  *10X*BWY     WIND DIRECTION       *F9.2* DEG*
     3/*  *10X*CO      SHIP COURSE          *F9.2* DEG,*I4* DEG *F5.1* MIN*
     4/*  *10X*CT      TARGET COURSE        *F9.2* DEG *
     5/*  *10X*DELU    IV CHANGE FROM STD   *F9.2* FT/SEC*
     6/*  *10X*DELUPD  DELU + DIDDLE        *F9.2* FT/SEC*
     7/*  *10X*DMHO    SHIP SPEED           *F9.2* KNOTS*
     8/*  *10X*DMHT    HORZ RANGE RATE      *F9.2* KNOTS*
     9/*  *10X*DMV     VERT RANGE RATE      *F9.2* YD/SEC*
     A/*  *10X*DMHX    E-W  RANGE RATE      *F9.2* YD/SEC*
     B/*  *10X*DMHY    N-S  RANGE RATE      *F9.2* YD/SEC*
     C/*  *10X*ED      DIRECTOR ELEVATION   *F9.2* DEG,*I4* DEG *F5.1* MIN*
     D/*  *10X*EI      LEVEL                *F9.2* DEG,*I4* DEG *F5.1* MIN*
     E/*  *10X*IV      INITIAL VELOCITY     *F9.2* FT/SEC*
     F/*  *10X*QEG     ELEVATION SPOT       *F9.2* DEG*
     G/*  *10X*QLH     DEFLECTION SPOT      *F9.2* DEG* )
  133 FORMAT(* *10X*QR4     RANGE SPOT             *F9.2* YD*
     I/*  *10X*QRHX    E-W OFFSET           *F9.2* YD*
     J/*  *10X*QRHY    N-S OFFSET           *F9.2* YD*
     K/*  *10X*R       RANGE                *F9.2* YD*
     L/*  *10X*TG      DEAD TIME            *F9.2* SEC*
     M/*  *10X*W       WEIGHT               *F9.2* LB*
     N/*  *10X*WH      WIND SPEED           *F9.2* KNOTS*
     O/*  *10X*XRHO    RHO CHANGE FROM STD*F9.2* PERCENT*
     P/*  *10X*XRHOPD  XRHO + DIDDLE        *F9.2* PERCENT*
```

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   Q/*  *10X*Y       TEMPERATURE           *F9.2* DEG F*
   R/*  *10X*Z       CROSS LEVEL           *F3.2* DEG,*I4* DEG * F5.1* MIN
   S*)
130 CONTINUE
    XDOT=XDOT*3.
    YDOT=YDOT*3.
    ZDOT=ZDOT*3.
    R=R*3.
    DS=DS/100.
    TS=TS/100.
104 FORMAT (7F10.3)
    IF(IPRNT.LE.2)PRINT 102,R,BD ,EI,ZD,CO, TGG,PVDP,PDD,PDA,ED,DMHO,
   A XDOT,
   1 YDOT,ZDOT,XDDOT,YDDOT,ZDDOT,U,WH,BWY,XL,W,DW,DS,TS,V4S,EG,DEIO,
   2 DCQO,DZO,T4,QRHX,QRHY,QLH,QEG,QRH4
102  FORMAT(* INPUTS*,
   1T010,*R   = *,F10.4,T030,*BD  = *,F10.4,T050,*EI  = *,F10.4,
   2T070,*ZC  = *,F10.4,T090,*CO  = *,F10.4,T110,*TGG =*,F10.4,/,* *,
   3T010,*PVDP=*,F10.4,T030,*PDD =*,F10.4,T050,*PDA =*,F10.4,
   4T070,*EC  = *,F10.4,T090,*DMHO=*,F10.4,T110,*XDCT=*,F10.4,/,* *,
   5T010,*YDOT=*,F10.4,T030,*ZDOT=*,F10.4,T050,*XDD =*,F10.4,
   6T070,*YDD =*,F10.4,T090,*ZDD =*,F10.4,T110,*U   = *,F10.4,/,* *,
   7T010,*WH  = *,F10.4,T030,*BWY =*,F10.4,T050,*XL  = *,F10.4,
   8T070,*W  =  *,F10.4,T090,*DW  = *,F10.4,T110,*DS  = *,F10.4,/,* *,
   9T010,*TS  = *,F10.4,T030,*V4S =*,F10.4,T050,*EG  = *,F10.4,
   AT070,*DEIO=*,F10.4,T090,*DCQO=*,F10.4,T110,*DZO =*,F10.4,/,* *,
   BT010,*T4  = *,F10.4,T030,*QRHX=*,F10.4,T050,*QRHY=*,F10.4,
   CT070,*QLH =*,F10.4,T090,*QEG =*,F10.4,T110,*QRH4=*,F10.4)
    TIM=SECOND(T1)
    DATA AA,BB/57.296,1.689/
    DMHO=BB*DMHO
    QLH=QLH/AA $ QEG=QEG/AA
    XL=XL/AA
    BD=BD/AA
```

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```
EI=EI/AA
ZO=ZO/AA
CO=CO/AA
EO=EO/AA
CQO=CO
EG=EO $ CEG=COS(EG) $ SEG=SIN(EG)
SBD=SIN(BD) $ CBD=COS(BD) $ SEI=SIN(EI) $ CEI=COS(EI)
SZD=SIN(ZD) $ CZD=COS(ZD)
                                      SCQO=SIN(CQO) $ CCQO=COS(CQO)
SCO=SIN(CO) $ CCO=COS(CO)
EIO=ASIN(SEI*CBD+CEI*SBD*SZD)
CEIO=COS(EIO) $ SEIO=SIN(EIO)
ZO=ASIN((CEI*SZD*CBD-SEI*SBD)/CEIO)
SZO=SIN(ZO) $ CZO=COS(ZO)
BY11=SBD*CZD $ BY22=CBD*CEI-SBD*SEI*SZD
B= ATAN2(BY11,BY22)
BY=CQO+B
E= EO-EI
QSTARZ=QHXS=QHYS=0.
Z=R*SIN(E)
RH=R*COS(E)
Y=RH*COS(BY) + QRHY
X=RH*SIN(BY) + QRHX
RH= SQRT(X*X + Y*Y) +QRH4
BY=ATAN2(X,Y)
B=BY-CQO
SB=SIN(B) $ CB=COS(B)
SZD=SB*CZO*SEIO+CB*SZO
ZD=ASIN(SZD)
CZD=COS(ZD)
SEI=(CB*CZO*SEIO-SZO*SB)/CZD
CEI=CZO*CEIO/CZD
TBDY=SB*CEI
TBDX=CB*CZD + SB*SEI*SZD
BD=ATAN2(TBDY,TBDX)
```

```
      CBD=COS(BD)  $ SBD=SIN(BD)
      X=RH*SIN(BY)
      Y=RH*COS(BY)
*   PARALLEX EQUATIONS
      PHO=PDO*CEIO +PVDP*SELO*CZO+PDA*SEIO*SZO
      PHA=PDA*CZO  - PVDP*SZO
      PV  =PVDP*CEIO*CZO+PDA*SZO*CEIO-PDO*SEIO
      PX   =PHO*SCQO+  PHA*CCQO
      PY   =PHO*CCQO-  PHA*SCQO
      WH=BB*WH
      BWY=BWY/AA
      WHY   =-WH*COS(BWY)
      WHX   =-WH*SIN(BWY)
      TG=TSG
      DU    =-AM*DW*U/W
      UCW   =U+DU
      DDS=-(DW/W)*DS
      DS=DS+DCS+PTO/100.
      BGY=BY
      N=2.
      V=SQRT(XDOT**2  + YDOT**2  + ZDOT**2)
      T4=  R/(U+V)
      IT5=0
      N2=0
  60  TGSQ=TG*TG
      IT5=IT5+1
      IF(IT5.GT.15) GO TO 50
      MXTG=XDOT*TG +XDDOT*TGSQ/2.
      MYTG=YDOT*TG +YDDOT*TGSQ/2.
      MZTG=ZDOT*TG +ZDDOT*TGSQ/2.
      XTG  =X  +MXTG-PX
      YTG  =Y  +MYTG-PY
      ZTG  =Z  +MZTG-PV
      BYTG=ATAN2(XTG,YTG)
      XDOTTG=XDOT+XDDOT*TG
```

```
      YDOTTG=YDOT+YDDOT*TG
      ZDOTTG=ZDOT+ZDDOT*TG
      N1=0
      NTEST=PTEST=0
   70 MTHX=(XDOTTG+XDDOT*T4/2.+DMHO*SCO)*T4
      MTHY=(YDOTTG+YDDOT*T4/2.+DMHO*CCO)*T4
      MTZ =(ZDOTTG+ZDDOT*T4/2.)*T4
      N1=N1+1
      IF(N1.GE.50) GO TO 143
      IF(MO.NE.3) GO TO 72
*    STAR SHELL CORRECTIONS
      XPRIM=XTG+(30.+T4)*(XDOTTG+XDDOT*(30.+T4)/2.)
      YPRIM=YTG+(30.+T4)*(YDOTTG+YDDOT*(30.+T4)/2.)
      RPRIM=SQRT(XPRIM*XPRIM+YPRIM*YPRIM)
   80  QSTARZ=2000. $ QSTARH=5400.
      QHXS=QSTARH*XPRIM/RPRIM
      QHYS=QSTARH*YPRIM/RPRIM
      MTHX=(XDOTTG+DMHO*SCO) * (T4+30.)  -WHX*30.+XDDOT*(30.+T4)**2/2.
      MTHY=(YDOTTG+DMHO*CCO) * (T4+30.)  -WHY*30.  +YDDOT*(30.+T4)**2/2.
   72 CONTINUE
      RHX2=XTG  +MTHX  + QHXS
      RHY2=YTG  +MTHY+QHYS
      RV2  =ZTG  +MTZ  + QSTARZ
      BY2  =ATAN2(RHX2,RHY2)
      R2   =SQRT(RHX2*RHX2+RHY2*RHY2+RV2*RV2)
      E2   =ASIN(RV2/R2)
*    GUN FIRE SOLUTION
      RV   =RV2
      RH2=ABS(R2*COS(E2))
*   GUN THROW
      DMHOG=PV*DEIO-RHA*DCQD
      DMHAG=-PV*DZO+RHO*DCQD
      BG=BGY-CQO   $ CBG=COS(BG)  $ SBG=SIN(BG)
      DMRHOG=DMHOG*CBG+DMHAG*SBG
      DMBOG= DMHAG*CBG-DMHOG*SBG
```

```
      DMVOG=-RHO*CEIO +PHA*DZO
      U=SQRT((UCW*CEG+DMRHOG)**2  +(UCW*SEG+DMVOG)**2 )
    + SBGY=SIN(BGY) $ CBGY=COS(BGY)
      IF(IT5.EQ.1) N2=N2+1
      IF(N2.GE.50) GO TO 149
      WRH   =WHY*CBGY   + WHX*SBGY
      W3    =-WHY*SBGY   + WHX*CBGY
* SHIP MOTION
      DMB   =DMHO*SIN(CO-BGY)
      RH4   =RH2 *COS(BGY-BY2)
      DMRH=LMHO*COS(CO-BGY)
   10 CONTINUE
   12 E4=ATAN(RV/RH4)

      CALL BALLIS(RH4,RV,TS,T44,EG,DRIFT,E4,WRH)

      IF(IFLAG.EQ.1)  GO TO 150
      IF(IPRNT.LE.1)  PRINT 103,RH4,RV,TS,T44,EG,DRIFT,E4,WRH,
     1 MTHX,MTHY,MTZ,RH2,RHX2,RHY2,RV2,EI,ZD,DTF
  103 FORMAT(* *,10(F10.4,2X),/,* *,10(F10.4,2X))

      CEG=COS(EG)
   17 CONTINUE
   18 EGY=-ATAN(MBG/RH4) +BY2
   20 LH    =BGY -BYTG       $ SLH=SIN(LH)   $ CLH= COS(LH)
      SEG=SIN(EG)
      DT4   =ABS(T44-T4)-TOL2
  521 FORMAT(* *,3(I5,2X),2X,5(F10.3,2X))
      IF(DT4)30,30,71
* CONVERGENCE METHOD
   71 CONTINUE
      RA(1)=RA(2) $ RA(2) =T44
      TA(1)=TA(2) $ TA(2)=T4
      DIF=T44-T4
      IF(DIF.GT.0.) GO TO 300
```

```
      NTEST=1
      R22=T44
      T22=T4
      GO TO 305
  300 PTEST=1
      R11=T44
      T11=T4
  305 CONTINUE
      IF(ABS(DIF).LE.1.) GO TO 310
      IF((NTEST+PTEST).NE.2) GO TO 310
      SN=(T11-T22)/(R11-R22)
      IF(ABS(SN).LT.0.1) GO TO 308
      ITEST=(1.1-SN)*(SN-.90)
      IF(ITEST)307,308,308
  307 T4=(T22-SN*R22)/(1.-SN)
      GO TO 70
  308 T4=T44
      GO TO 70
  310 CONTINUE
      IF(N1.GT.1) GO TO 311
      GO TO 308
  311 SN=(TA(1)-TA(2))/(RA(1)-RA(2))
      IF(ABS(SN).LT.0.1) GO TO 308
      ITEST=(1.1-SN)*(SN-.9)
      IF(ITEST) 309,308,308
  309 CONTINUE
      T4=(TA(2)-SN*RA(2))/(1.-SN)
      GO TO 70

   70 CONTINUE
      T4=T44
      IF(TG.EQ.TGG)T5=T4
 5001 CONTINUE
  501 FORMAT(* *,I2,2X,7(F8.1,2X),3(F8.3,2X),3(F8.2,2X))
      IF(TG.NE.0.0)GO TO 40
```

```
      GO TO 50
   40 TG=0.
      GO TO 60
   50 CONTINUE
      IF(MC.EQ.9.) T5=T5-1./2
      LH=LH+QLH  $  EG=EG+QEG
      SLH=SIN(LH) $ CLH= COS(LH) $ SEG=SIN(EG) $ CEG=COS(EG)
      EDGP =ASIN(-SZD*SLH*CEG+CZD*(SEI*CEG*CLH+SEG*CEI))
      LDP  =ATAN((CZD*SLH*CEG+SZD*(SEI*CEG*CLH+SEG*CEI))
     1      /(CEG*CEI*CLH-SEG*SEI))
      BDGP =LDP +SD
      TIM=SECOND(T2)
      TIME=T2-T1
      EDGPX=EDGP*57.296*60.
      BDGPX=BDGP*57.296*60.
      IF(BDGPX.LT.0.)BDGPX=21600.+BDGPX
      I=INUM
      DT5=T5OF(I)-T5
      DBDGP=BDGPOF(I) -BDGPX
      DEDGP=EDGPOP(I) -EDGPX
      IF(IPRNT.LE.2) PRINT 201,GAMMA
  201 FORMAT(* GAMMA= *F7.3)
      IF(IPRNT.LE.2)PRINT 200,NO(INUM),T5OP(I),T5,DT5,BDGPOP(I),BDGPX,
     A DBDGP,
     1 EDGPOP(I),EDGPX,DEDGP,TIME,N1,N2,MO,J
  200 FORMAT(* *,T4,I2,5X,F6.3,2X,F6.3,1X,F6.3,4X,2(F7.1,1X),F6.1,4X,
     1 2(F6.1,1X),F6.1,5X,F8.3,5X,I2,4X,I2,9X,I2,3X,I2,/)
      IF(IPRNT.NE.5)GO TO 135

      BGYN=BGY*AA
      IF(BGYN.LT.0.0)BGYN=360.+BGYN
      IBGY=BGYN
      DBGY=(BGYN-IBGY)*60.
      BYN =BY*AA
      IF(BYN.LT.0.0)BYN=360.+BYN
```

```
      IBY  =BYN
      DBY  =(BYN-IBY)*60.
      EN   =E*AA
      IE   =EN
      DE  =(EN-IE)*60.
      E4N=E4*AA
      IE4=E4N
      DE4=(E4N-IE4)*60.
      LHN=LH*1000.+500.
      IF(LHN.GT.6283.19) LHN=LHN-2.*3.14159
      R4=SQRT(RV*RV+RH4*RH4)
      R4N=R4/3.
      IF(MO.EQ.3) R4N=R4N/1.2
      RHXN=   X/3.
      RHYN=   Y/3.
      RVN  =  Z/3.
      V4=EG-E4
      V4N  =V4*AA*60.
      V4NRD=V4N  +2000.
      PRINT 136      ,IBGY,DBGY     ,IBY,DBY    ,IE,DE     ,IE4,DE4,GAMMA
      PRINT 134,LHN, R4N,RHXN,RHYN,RVN,V4N, V4NRD
  136 FORMAT(* *8X*INTERMEDIATE OUTPUTS*
     A/*+*8X*____________________*
     1/* *10X*BGY     GUN BEARING         *I4* DEG *F5.1* MIN*,
     2      T56*_____DEG _____MIN*
     4/* *10X*BY      TARGET BEARING      *I4* DEG *F5.1* MIN*,
     2      T56*_____DEG _____MIN*
     7/* *10X*E       TARGET ELEVATION    *I4* DEG *F5.1* MIN*,
     2      T56*_____DEG _____MIN*
     A/* *10X*E4      ELEVATION LOS       *I4* DEG *F5.1* MIN*,
     2      T56*_____DEG _____MIN*
     D/* *10X*GAMMA   REC BALLISTIC COEFF*F9.4  )
  134 FORMAT(* *10X*LH      HORIZ DEFLECTION    *F9.4* MILS*
     F      T58*________MILS *
     H/* *10X*R4      AIM PT.RANGE(SCALE)*F9.2* YD*
```

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```
I       T58*________YDS*
K/*  *10X*RHX      E-W RANGE              *F9.2* YD*
L       T58*________YDS*
N/*  *10X*RHY      N-S RANGE              *F9.2* YD*
O       T58*________YDS*
Q/*  *10X*RV       ALTITUDE               *F9.2* YD*
R     T58*________YDS*
T/*  *10X*V4       SUPER ELEVATION        *F9.2* MIN*
W/*  *10X*V4P      V4+200)                *F9.2* MIN*
Y     T58*________MIN*)
     EDGPN=EDGP*AA*60.+2000.
     BDGPN=BDGP*AA
     IF(BDGPN.LT.0.0) BDGPN=360.+BDGPN
     IBDGP=BDGPN
     DBDGP=(BDGPN-IBDGP)*60.
     PRINT 137,IBDGP,DBDGP,EDGPN,T5,T4
 137 FORMAT(* *8X*OUTPUT*
    A/*+*8X*______*
    1/*  *10X*BDGP     GUN BEARING ORDER   *I4* DEG *F5.1* MIN*
    2       T56*_____DEG _____MIN*
    4/*  *10X*EDGP     GUN ELEVATION ORDER*F9.2* MIN*
    2       T56*_____DEG _____MIN*
    7/*  *10X*T5       FUZE ORDER             *F9.4* SEC*
    7       T58*________SEC*
    7/*  *10X*T2       TIME OF FLIGHT          *F9.4* SEC*
    8     T58*________SEC*    /)

 135 CONTINUE
2007 FORMAT(* *,6(F10.2,2X))
     GO TO 150
 149 PRINT 148,INUM,N1,N2
 148 FORMAT(*0PROBLEM NO*,I3,* DID NOT CONV*,I3,*T2 PASSES*,
    1 I3,* T5 PASSES*)
 150 CONTINUE
 151 CONTINUE
```

```
  107 FORMAT(*-      MODE SELECTED FOR THIS RUN WAS---*,A10,*---*)
      DATA NEME/9H5 INCH AA,8HNOT USED,10H5 INCH SUR,10H5 INCH REV,
     1 10HHIGH ANGLE,3*(8HNOT USED),9H5 IN STAR,8HWHITE RH/
 1007 FORMAT(* *, A10,/* *,A10,A10)
     1 = *,I2)
 1008 FORMAT(*        COMPARISION FROM OP*,I5,* FOR MOD*,I3,* MK47*)
      WHEN=DATE(D)
      PRINT 1009,WHEN
 1009 FORMAT(* *,8X,A9)
  101 FORMAT(* *,I5,2X,4(F10.4,2X))
      END
```

```
      SUBROUTINE BALLIS(RH4,RV,TS,T44,EG,DRIFT,F4,WRH)
      COMMON/ONE/MO,IATM
      COMMON/TWO/DEIN(9),DEOUT(9),H,ZMAX
      COMMON/THREE/CM,DRAGO,DRAG(144),VAA(144),ICD
      COMMON/FOUR/TM
      COMMON/FIVE/PNAME
      COMMON/SIX/ICONT,TK,WKX
      COMMON/SEVEN/U,DMRH
      COMMON/EIGHT/IFLAG
      COMMON/TEN/IPRNT
      COMMON/ELEVEN/WB,AX,AY,AZ,XL,BGY,DMB,DMBOS,MBG,CANS,GAMMA
      COMMON/TWELVE/G,CSS,ICOP
      REAL MBG
      DATA TO,XO,ZO,YO/04*0./
      WXX=WRH
*  FIRST EG GUESS
      AX=-.00014584*COS(XL)*COS(BGY)
      AY=+.00014584*COS(XL)*SIN(BGY)
      AZ=-.00014584*SIN(XL)
      SR=SQRT(RH4*RH4+RV*RV)
      IF(ICOR.EQ.1) AX=AY=AZ=0.0
      ANG=64.4*RH4/(U*U)
      IF(ABS(ANG).GT.1.0) ANG=1.0
      EG=ATAN2(RV,RH4)+.5*ASIN(ANG)
      IF(MO.EQ.5) EG=1.57-EG
      N=0
 3000 CONTINUE
$$$ GAMMA VARIES WITH QE FOR REDUCED CHARGE MK 41
      DATA NMK41/4HMK41/
      IF((MO.EQ.4).A.(PNAME.EQ.NMK41))GAMMA=1./(2.994-.0081*57.296*EG)
      IF((MO.EQ.4).A.(EG.LE.0.524).A.(PNAME.EQ.NMK41)) GAMMA=1./2.75
$$$ GAMMA VARIES WITH QE FOR MK 48 WHITE PHOS.
      IF(MO.EQ.10)GAMMA=1./(2.552-.0032*57.296*EG)
      N=N+1
      IF(N.GT.20) GO TO 100
```

```
      GO TO 101
  100 PRINT 99,EG,TM,H,T44,DRIFT,DZ,RV,SP
   99 FORMAT(* *,10(F10.4,1X))
      IFLAG=1
      IF(N.GT.25) GO TO 5003
  101 CONTINUE
 5003 FORMAT(* *,70X,I5,2X,F10.3)

      ICONT=1
      TM=TS*100.
      TK=.55556*TM+255.222
      DEOUT(1)=1.
      DEIN(1)=T0
      DEIN(2)=X0
      DEIN(3)=Z0
      DEIN(4)=U*COS(EG)+DMR4
      DEIN(5)=U*SIN(EG)
      DEIN(6)=0.
      DEIN(7)=0.
      DEIN(8)=Y0
      DEIN(9)=DM0+DMBOG
      H=1.
      IF(MC.EQ.5) GO TO 2102
      GO TO 102

 2102 CALL RUNKUT
      ICONT=2
      IF(DEIN(3)-RV)2125,2113,2102
 2125 H=-(DEIN(3)-RV)/DEIN(5)
      CALL RUNKUT
      IF(ABS(DEIN(3)-RV)-.1)2113,2113,2125
 2113 CONTINUE
      GO TO 113

  102 CALL RUNKUT
```

```
      ICONT=2
      IF(DEIN(2)-RH4) 102,113,1125
1125  H=(RH4-DEIN(2))/ABS(DEIN(4))
      CALL RUNKUT
      IF(ABS(DEIN(2)-RH4)-.1)113,113,1125
 113  CONTINUE
      T44=DEIN(1)
1131  CONTINUE
 114  DRIFT=CANG*(DEIN(2)*DEIN(6)-DEIN(7))
      MBG=DRIFT+DEIN(8)
      IF(MC.EQ.5) GO TO 2050
      GO TO 2060
2050  CONTINUE
      DX=RH4-DEIN(2)
      IF(ABS(DX).LE.0.1) GO TO 6000
      SR=SQRT(DEIN(2)**2 + DEIN(3)**2)
      IF(SR.EQ.0.0) GO TO 5002
      DELEG=ATAN(DX*COS(EG)/RH4)
      IF(IPRNT.EQ.0) PRINT 4000,N,EG,DELEG,T44,DZ,SR
      EG=EG+DELEG
      IF(EG.GE.1.57) GO TO 6000
      IF(EG.LT.0.785) GO TO 6000
      GO TO 3000
2060  CONTINUE
      DZ=RV-DEIN(3)
      IF(ABS(DZ).LE.0.1) GO TO 6000
       SR=SQRT(DEIN(2)**2 + DEIN(3)**2)
      IF(SR.EQ.0.0) GO TO 5002
      DELEG=ATAN(DZ*COS(E4)/SR)
      IF(IPRNT.EQ.0) PRINT 4000,N,EG,DELEG,T44,DZ,SR
4000  FORMAT(* *,I4,9(2X,F10.4))
      EG=EG+DELEG
      IF(EG.GE.1.57) GO TO 6000
      GO TO 3000
5002  CONTINUE
```

```
      EG=EG+.1
      IF(EG.GE.1.57) GO TO 5000
      GO TO 3000
 6000  CONTINUE
 5000 CONTINUE

      IF(IPRNT.EQ.0) PRINT 4300,N,EG,DELEG,T44,DZ,SR
      END
```

```
      SUBROUTINE BUNKUT
      COMMON/ONE/MO,IATM
      COMMON/TWO/DEIN(9),DEOUT(9),H,ZMAX
      COMMON/THREE/CM,DRAGC,DRAG(144),VAA(144),TCD
      COMMON/FOUR/TM
      COMMON/SIX/ICONT,TK,WK
      COMMON/NINE/DS
      COMMON/ELEVEN/WB,AX,AY,AZ,XL,BGY,DMB,DMBOG,MBG,CANS,GAMMA
      COMMON/TWELVE/G,CSS,ICOR
      DIMENSION DE1(9),DE2(9)
      DATA RE/20855531./
 1008 FORMAT (49H COMPUTED MACH NO. EXCEEDS MACH NO. OF DRAG TABL.)
 1009 FORMAT (8E15.8)
      M1=4
      JGO=ICONT
      GO TO (300,67),JGO
   67 M1=1
   68 DO 298 I=1,9
      GO TO (294,295,296,297,299),M1
  294 DE1(I)=DEIN(I)
      DE2(I)=DEOUT(I)*H
      E1=DE2(I)*.5
      GO TO 298
  295 E1=DEOUT(I)*.5*H
      DE2(I)=DE2(I)+4.*E1
      GO TO 298
  296 E1=DEOUT(I)*H
      DE2(I)=DE2(I)+E1+E1
      GO TO 298
  297 E1=(DE2(I)+DEOUT(I)*H)/6.
  298 DEIN(I)=DE1(I)+E1
  300 XW=DEIN(4)-WX
      YW=DEIN(9)-WB
      ZW=DEIN(5)
      VA=SQRT(XW*XW+YW*YW+ZW*ZW)
```

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      ALT=DEIN(3)+DEIN(2)*DEIN(2)/(2.*RE)
      IF(IATM.EQ.2) GO TO 500

C    NAVY STANDARD ATMOS
      IF(ALT.LT.0.) ALT=0.
      T=TK-.001982*ALT
      CS=1120.*SQRT(T/288.)
      CM=VA/CS
      RHO=(.07513*EXP(-.000031682*ALT))*DS
      GO TO 2114

C     ICAO ATMOSPHERE
  500 CONTINUE
      TD=TM-59.
      GALT= RE*ALT/(RE+ALT)
      IF(GALT.GE.36089.) GO TO 502
      TR=518.67-.00356616*GALT
      P=1013.25*(518.67/TR)**(-5.255877)
      GO TO 505
  502 IF(GALT.GT.65616.8) GO TO 504
      TR=389.97
      P=226.32*EXP(-.0000480634*(GALT        -36089.239) )
      GO TO 505
  504 TR=389.97+.00054864*(GALT-65616.789)
      P=54.7487*(389.97/TR)**34.16319
  505 CONTINUE
      RHO=.0391462*P*CS/TR
      CS=1116.44*SQRT((TR+TD)/518.67)
      CM=VA/CS
 2114 I=1
      IF(CM-VAA(I))2115,2115,2116
 2115 DRAGC=DRAG(I)
      GO TO 2119
 2116 DO 2117 I=2,144
      IF(CM-VAA(I)) 2118,2115,2117
```

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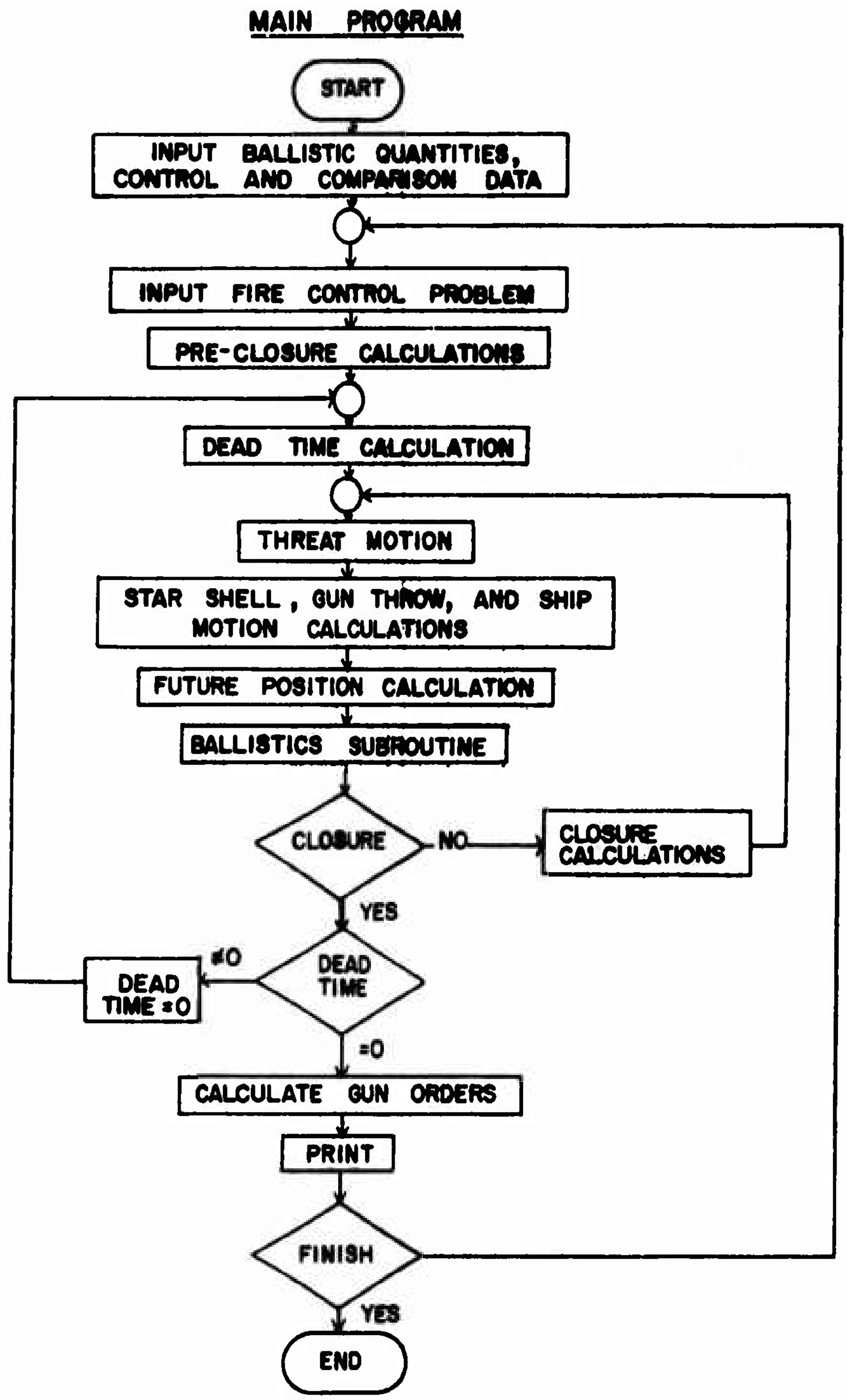
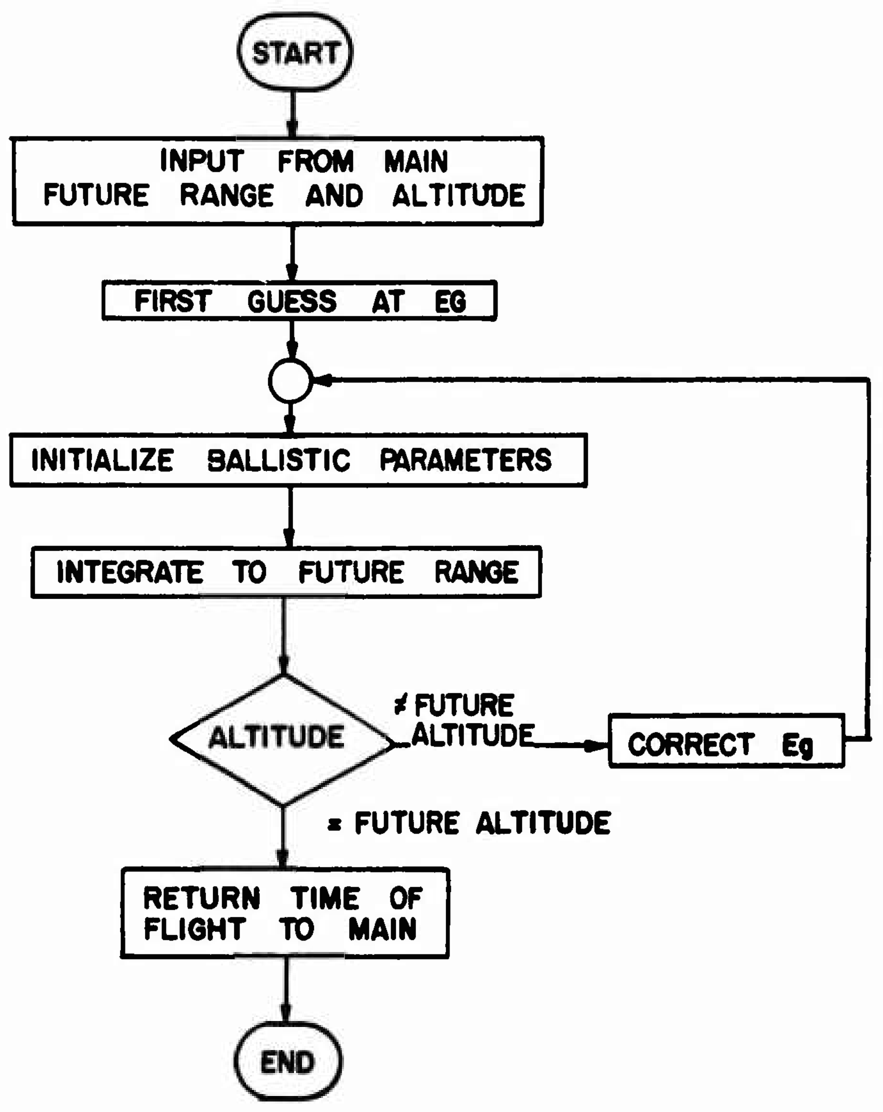
```
2117 CONTINUE
     PRINT 1003
     PRINT 1009,(DEIN(I),I=1,5),VA,CS,CM,RHO
     STOP
2114 DRAGC=DRAG(I-1)+((C1-VAA(I-1))/(VAA(I)-VAA(I-1)))*(DRAG(I)-
    1  DRAG(I-1))
2119 DRAGC=.39269908*DRAGC
     CONS=-GAMMA*RHO*VA*DRAGC/144.
     DEOUT(2)=DEIN(4)
     DEOUT(3)=DEIN(5)
     DEOUT(4)=CONS*XW-(AY*DEIN(6)-AZ*DEIN(9))-G*DEIN(2)/RE
     DEOUT(5)=CONS*DEIN(5)-(AX*DEIN(9)-AY*DEIN(4))-G+2.*G*DEIN(3)/RE
     DEOUT(6)=1./(VA*VA)
     DEOUT(7)=DEIN(2)/(VA*VA)
     DEOUT(8)=DEIN(9)
     DEOUT(9)=CONS*YW-(AZ*DEIN(4)-AX*DEIN(5))-G*DEIN(8)/RE
     M1=M1+1
     GO TO 69
 299 RETURN
     END
```

APPENDIX B

FLOW DIAGRAM


MAIN PROGRAM
START
INPUT BALLISTIC QUANTITIES, CONTROL AND COMPARISON DATA
INPUT FIRE CONTROL PROBLEM
PRE-CLOSURE CALCULATIONS
DEAD TIME CALCULATION
THREAT MOTION
STAR SHELL, GUN THROW, AND SHIP MOTION CALCULATIONS
FUTURE POSITION CALCULATION
BALLISTICS SUBROUTINE
CLOSURE
NO
CLOSURE CALCULATIONS
YES
≠0
DEAD TIME
DEAD TIME =0
=0
CALCULATE GUN ORDERS
PRINT
FINISH
YES
END

BALLISTIC SUBROUTINE



APPENDIX C

INPUT GUIDE

INPUT GUIDE

Card Group	Card	Column	Format	Symbol	Description
1	1	1-10	A4	PNAME	Projectile type
	2	1-6	F6.4	CANS	Projectile drift constant
		7-12	F6.4	GAMMA	Reciprocal ballistic coefficient
		13-18	F6.4	G	Sea level acceleration of gravity (ft/sec^2)
		19-24	F6.4	CSS	Sea level velocity of sound (ft/sec)
		25-30	F6.4	AM	Projectile weight correction factor
		31-36	F6.4	PTO	Projectile-fuze correction factor (%)
2	1	1-5	I5	NX	Number of ıg coefficient pairs
3	1	1-72	12F6.4	VAA(I)	Mach numbers in ascending order (NX values, 12 per card)
	2				
	.	.	.		
	.	.	.		
	.	.	.		
4	1	1-72	12F6.4	DRAG(I)	Drag coefficient (CD) corresponding to VAA(I) (NX values, 12 per card)
5	1	1-5	I5	MO	Mode: 1, AA; 3, surface, regular charge; 4, surface, reduced charge; 10, MK 48 WP
	2	1-5	I5	IATM	Type of atmosphere: 1, NAST; 2, ICAO
	3	1-5	I5	ICOR	Coriolis type: 1, none; 2, with
	4	1-5	I5	IPRNT	Print type: 0, most; 1, more; 2, least; 5, table
	5	1-5	I5	IDID	Diddle type: 1, without; 2, with*; 3, with
	6	1-5	I5	NUMB	Number of problems to be run
6	1	1-5	I5	IDEN	Identification number of problem

*Not used in any calculations. Used only in print out.

Card Group	Card	Column	Format	Symbol	Description
	2	1-10	F10.3	BD	Director bearing (deg)
		11-20	F10.3	BWY	Wind direction (deg)
		21-30	F10.3	CO	Ship course (deg)
		31-40	F10.3	DMHO	Ship speed (kt)
		41-50	F10.3	Ed	Director elevation (deg)
		51-60	F10.3	Ei	Level angle (deg)
		61-70	F10.3	IV	Initial velocity (ft/sec)
	3	1-10	F10.3	PDO	Gun parallax along ship's centerline (ft)
		11-20	F10.3	PT	Projectile type (%)
		21-30	F10.3	PVDP	Vertical parallax (ft)
		31-40	F10.3	R	Target range (yd)
		41-50	F10.3	RHO	Air density (%)
		51-60	F10.3	TEM	Air temperature (°F)
		61-70	F10.3	TG	Dead time (sec)
	4	1-10	F10.3	W	Projectile weight (lb)
		11-20	F10.3	WH	Wind speed (kt)
		21-30	F10.3	ZD	Cross level (deg)
		31-40	F10.3	DMV	Vertical target velocity (ft/sec)
		41-50	F10.3	DMhx	East-west target velocity (ft/sec)
		51-60	F10.3	DMhy	North-south target velocity (ft/sec)
		61-70	F10.3	T5OP	Fuze time (sec)**
	5	1-10	F10.3	EDGPOP	Elevation gun order (min)**
		11-20	F10.3	BDGPOP	Bearing gun order (min)**

The user now repeats the 5 cards of card group 6 until "NUMB" input sets have been provided.

**These three input values will be compared to the actual results of the gunfire control solution in the IPRINT = 2 print option. They do not alter the calculations.